Journal of Cleaner Production 212 (2019) 1044–1053

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Embodied energy and greenhouse gas emissions analysis of a prefabricated modular house: The "Moby" case study

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ARTICLE INFO

Article history:
Received 13 July 2018
Received in revised form
30 November 2018
Accepted 3 December 2018
Available online 4 December 2018

Keywords:
Offsite construction
Residential building
Life-cycle assessment (LCA)
Embodied energy (EE)
Climate change

ABSTRACT

Buildings are big consumers of energy and materials, and important producers of waste and emissions. Prefabrication presents an opportunity to reduce impacts in the building sector; however, few studies have focused on prefabricated houses and with contradictory findings. The main goal of this article is to assess the embodied energy (EE) and greenhouse gas emissions (GHG) of a prefabricated modular house, based on a modular system to enable different layouts. A "cradle-to-site" analysis was performed, including materials production, transport to plant, modules' production, transport to site and final assemblage on site. Several house final locations were addressed to assess transport related impacts. Scenarios for alternative building structural materials (steel; concrete; timber and light steel framing (LSF)) and house size (bedroom number) were also analyzed, aiming at understanding the influence of these aspects in the results, and representing other prefabricated modular houses currently produced in Europe. The calculated embodied impacts show that materials production is the most important phase (64–90% of EE and 59–87% of GHG) and that the structures with LSF framing or timber have the lowest impacts, while steel and concrete the highest. Embodied impacts increase with the house size; however, a larger house leads to lower impacts per inhabitant, but similar impacts per m^2 (similar conclusion could be drawn for non-prefab buildings). The impacts of transportation (of modules, workers and finishing materials) vary significantly for the various house final locations and can be significant for overseas locations, which can jeopardize the potential benefits of modular prefabrication.

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1. Introduction

Buildings are big consumers of energy and materials, and important producers of waste and emissions. In Europe, buildings' construction and use account for half of the energy consumption and extracted materials (Vitale et al., 2017). A growing number of studies have been published about the environmental impacts of buildings; however, very few have focused on building prefabrication. Prefabrication is foreseen as one possible way to reduce costs, construction time, energy and environmental impacts in the building sector. Prefabrication is based on the production and pre-assembly of components, elements, panels or modules in the plant before assembly in the final house location. There are different types of prefabrication: component manufacture and sub-assembly (such as windows, doors or equipment), non-volumetric pre-assembly (panelized wall or timber trusts), volumetric pre-assembly (toilets or bathroom pods) and modular building (complete built units or modules that compose the whole building) (Kamali and Hewage, 2016). Different degrees of prefabrication can be employed, from prefabricated elements (façade, form, slab, balcony, staircase, and panel) to modules or full prefabricated buildings. As the level of prefabrication increases, the use of materials, energy and greenhouse gas (GHG) emissions decreases (Hong et al., 2016; Mao et al., 2013; Pons and Wadel, 2011).

Most studies assessing prefabricated buildings discuss the importance of the use phase (e.g., Adalberth, 1997; Atmaca and Atmaca, 2016; Bonamente et al., 2014); however, embodied impacts become more relevant as buildings become more energy efficient. Embodied energy can represent as much as 40% of total energy (Thormark, 2002, for a low energy consumption building). Therefore, there is a need to reduce buildings' embodied impacts

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https://doi.org/10.1016/j.jclepro.2018.12.028
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and prefabrication presents an opportunity to reduce the energy and resource intensive building process.

This article presents an energy and GHG analysis of a prefabricated house named “Moby”, which is based on a modular system to enable different layouts (area and inhabitants). A “cradle-to-site” analysis was performed, including materials production, transport to plant, modules production, transport to site and final assemblage on site. Several house final locations (national and overseas) were addressed to assess transport related impacts. Scenarios for alternative building structural materials and house sizes (bedroom number) were also analyzed, aiming at understanding the influence of these aspects in the results, and representing other prefabricated modular houses currently produced in Europe. The main goal is to quantify the embodied primary energy requirements and GHG intensity of the Moby prefabricated modular house, assessing the contribution of each phase and the influence of distance from plant to site. The following sections review recent studies of prefabricated buildings, describe the “Moby” prefabricated modular house (and alternatives), present and discuss results and draw the conclusions together.

1.1. Background

Research over the environmental impacts of buildings has been presented in the last decades, but only a few (and in general more recently) publications have addressed prefabricated buildings. Table 1 shows an overview of studies that assessed the embodied impacts of prefabricated buildings and lists embodied energy (EE) and GHG per house living area, construction type and location, building type and alternatives assessed. Fig. 1 compares the embodied impacts of prefabricated buildings per type of structural material for the studies presented in Table 1.

The impacts range from 1.75 to 14.4 GJ/m^2 for energy and from 211 to 1000 kg CO_2eq/m^2 for GHG. Timber and concrete buildings and container houses have the lowest impacts and steel the highest. The lowest impacts are reported for timber houses in the first article to assess prefabrication (Adalberth, 1997); for container houses (Atmaca and Atmaca, 2016; Islam et al., 2016); and in articles focusing only in parts of the buildings such as structural frame (Heravi et al., 2016) or elements that differ between modular and conventional buildings (Quale et al., 2012). The highest impacts are for prefabricated steel (Aye et al., 2012; Bonamente et al., 2014) and non-prefabricated buildings (Monahan and Powell, 2011; Pons and Wadel, 2011). Moreover, Bonamente et al. (2014) and Adalberth (1997) showed that buildings with bigger areas have lower impacts per m^2. Table 1 show that the embodied impacts (EE/m^2 and GHG/m^2) for prefabricated buildings are generally lower than for non-prefabricated buildings (Aye et al., 2012; Cao et al., 2014; Hong et al., 2016; Monahan and Powell, 2011; Pons and Wadel, 2011; Quale et al., 2012; Vitale et al., 2018). An exception occurs for prefabricated steel buildings that show similar or even higher impacts of the non-prefab buildings (Aye et al., 2012; Pons and Wadel, 2011). This emphasizes the need to assess and compare prefabricated buildings with alternative structural materials.

Pons and Wadel (2011) compared prefabricated schools (concrete, steel, and timber) with non-prefabricated ones and concluded that prefabricated schools had slightly fewer impacts, which can be further reduced since the current level of industrialization of prefabricated companies is low. The steel and concrete schools have higher impacts during extraction and fabrication phase, and timber and steel schools during transport and maintenance. Vitale et al. (2018) compared an LSF detached house with a conventional reinforced concrete house. Monahan and Powell (2011) analyzed the embodied energy and carbon of prefabricated houses built with three alternative structural materials (timber frame with larch cladding, timber frame with brick cladding, and conventional masonry) and concluded that materials are responsible for around 80% of embodied impacts mainly related to the substructure, foundations and ground floor. Aye et al. (2012) compared a conventional concrete house with two prefabricated houses (steel and timber) and, contrary to most studies, concluded that conventional concrete has the lowest embodied impacts while the prefabricated steel house has the highest. The contradictory results presented in the literature emphasize the need to further analyze prefabrication as a process to reduce buildings environmental burdens.

Three studies addressed partially prefabricated buildings (buildings parts or components that are prefabricated and used in a non-prefabricated building process). Cao et al. (2014) compared a partially prefabricated residential building with a traditional one with similar characteristics (floor area, structural system, location, and technical features). Although prefabrication was only 38% of the total building concrete volume, it resulted in a significant reduction of waste and materials (mortar, timber, heat insulation and steel, though increasing concrete) leading to a decrease of resource depletion (−36%), health damage (−7%) and ecosystem damage (−5%). Hong et al. (2016) showed that prefabricated components (façade, form, slab, balcony, staircase, and panel) reduce waste and energy in comparison with the conventional construction method. Finally, Mao et al. (2013) compared a semi-prefabricated residential building with a conventional building, concluding that the higher the level of prefabrication, the lesser the amount of building materials needed and GHG emissions, but highlighted that this could only be achieved by minimizing transportation impacts.

Only a few studies have addressed modular prefabricated buildings. Quale et al. (2012) compared a four-module house and a conventional one with similar materials and showed that on-site construction has 20–70% higher impacts than modular construction (but calculated a significant variation of impacts within modular). Pons and Wadel (2011) (mentioned above for non-modular prefabricated buildings) also assessed modular prefabricated steel schools (containing structure, façade, pavement, interior walls and services) concluding that modular prefabrication is the best technology and with the higher level of prefabrication, even though some manual processes and transport related impacts could be improved. Kim (2008) compared a modular and a conventional single-family house in Michigan showing that the modular house construction generated 2.5 times less solid waste. Kamali et Hewage (2016) presented a critical review of studies focusing on the life cycle performance of modular buildings and emphasized the need to develop further studies that quantitatively account and balance the benefits and challenges of modular construction techniques.

A particular but emergent type of modular prefabricated buildings is based on the adaptation of shipping containers to houses. Atmaca and Atmaca (2016), focusing on temporary post-disaster buildings, showed that a prefabricated house with steel profiles and wall panels has 25% less impacts and 30% lower cost than a container house. Islam et al. (2016) assessed a 3-bedroom double story steel container house built in Melbourne. The system boundary for embodied impacts included raw materials, manufacturing of building components, transportation, and construction work; however, the impact of the shipping container was excluded, since it was assumed as an ‘upcycled material’ (i.e., reused with minimal modification for another purpose). In Table 1 container houses show the lowest embodied energy and GHG per m^2.

In prefabricated construction, impacts associated with transportation can be significant as prefabrication requires an extra

Table 1
Overview of studies focusing on the embodied impacts of prefabricated buildings.

Reference	Construction type	Location	Distance plant to site (km)	Building type	Structural material/Alternatives	Embodied energy/ m^2 (GJ/m^2)	Embodied GHG/m^2 ($kgCO_2eq/m^2$)
Adalberth, 1997	Prefabricated	Sweden	–	Residential	Timber house 1 (1-floor 130m^2)	3.7	–
					Timber house 2 (1-floor 129 m^2)	3.5	–
					Timber house 3 (2-floor 138m^2)	2.9	–
Achenbach et al. (2017)	Prefabricated	Germany	350	Residential	Timber average single and double family house (143 m^2)	–	213
Pons and Wadel (2011)	Prefab and conventional	Catalonia, Spain	100–300	Educational	Non-prefabricated	–	752
					Concrete	–	692
					Timber	–	526
					Steel	–	852
Monahan and Powell (2011)	Panelized Modular and conventional	Norfolk United Kingdom	213 (9372 tkm)	Residential	Timber frame larch cladding	5.7	405
					Timber frame brick cladding	7.7	535
					Conventional masonry	8.2	612
Quale et al. (2012)	Modular and conventional	USA	483 (300 mi)	Residential	Timber modular	–	73*
					Timber conventional	–	105*
Aye et al. (2012)	Prefab and conventional	Australia	–	Residential	Concrete (convent.)	9.6	578
					Steel (prefab)	14 .4	864
					Timber(prefab)	10.5	630
Mao et al. (2013)	Partially prefab and conventional	Shenzhen, China	45–95	Residential	Concrete semi-prefabrication	–	336
					Concrete conventional	–	368
Bonamente et al. (2014)	Prefab	Perugia, Italy	–	Industrial	Steel 1000 m^2	14	895
					Steel 2500 m^2	12.8	821
					Steel 5000 m^2	12.2	783
					Steel 10 000 m^2	11.8	757
					Steel 20 000 m^2	11.5	738
Cao et al. (2014)	Partially prefab and conventional	Beijing, China	–	Residential	Concrete precast	–	–
					Concrete traditional		
Hong et al. (2016)	Partially prefab and conventional	China	100	Residential	Concrete & steel precast facade	–	–
					Concrete & steel Precast form		
					Concrete slab		
					Concrete Balcony		
					Concrete Staircase		
					Concrete Panel		
Atmaca and Atmaca, 2016	Prefabricated and container	Turkey	100	Residential	Concrete and aluminum sheet prefabricated	4.1	–
					Concrete and steel sheet container	3.2	–
Islam et al. (2016)	Container	Melbourne, Australia	100	Residential	Steel container base case	3.24	211
					Steel container 100 y lifespan	3.24	211
					Steel container 100 km transportation	3.31	215
					Steel container low maintenance	3.24	211
Heravi et al. (2016)	Prefabricated	Tehran, Iran	100	Residential	Concrete frame	1.75–3.01**	–
					Steel frame	2.36–4.16**	–
Vitale et al. (2018)	Prefab and conventional	Campania, Italy	15–900	Residential	Prefab LSF	9.9	923
					Traditional concrete	8.5	

*Took into account only the building materials whose amounts differed between construction methods.
**Only considered the concrete and steel frame of 4 to 10-story buildings.

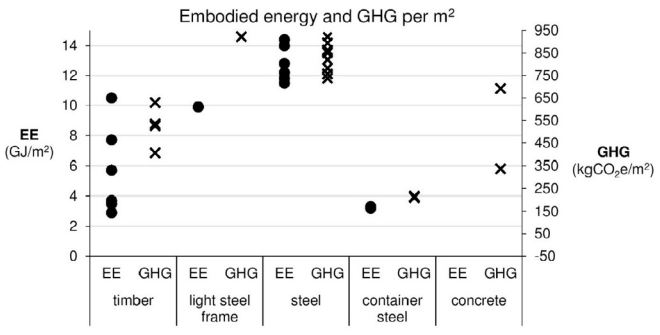

Fig. 1. Embodied energy (EE) and GHG of prefabricated buildings reported in Table 1.

transportation phase (from plant to site), extra load and unload processes (from the factory into the site) and extra material and clamps (for careful handling and transport avoiding damage) (Hong et al., 2016). However, most studies calculated relatively low transport related impacts, assuming low (typically from 50 to 100 km) or no distance at all from plant to the site (Adalberth, 1997; Aye et al., 2012; Bonamente et al., 2014; Cao et al., 2014). A brief discussion of exceptions follows. Monahan and Powell (2011) reported distances from plant to site about 200 km and Quale et al. (2012) almost 500 km. Vitale et al. (2018) reported from 15 to 900 km, Achenbach et al. (2018) 350 km and Pons and Wadel (2011) reported distances within 100–300 km, with two exceptions: 900 km for a modular steel structure and 1600 km for a timber structure and concluded that steel had the highest transport related impacts due to remote plant location and modularity. As mentioned by Achenbach et al. (2018), the transportation impacts cannot be neglected, as they can represent up to 20% of total embodied impacts.

Transport-related impacts are influenced not only by the distance from plant to site but also by the prefabrication type. Particularly for modular construction, transport is a critical issue limiting the dimension and weight of the modules, distance, transport mode and routes (Kamali and Hewage, 2016). Pons and Wadel (2011) discussed how modular buildings could have significant transport related impacts due to the high volume of the

finished modules (requiring one truck for each module). Quale et al. (2012) showed that transport to the site of modules and workers represented around 20% of embodied GHG.

Prefabricated houses are a promising technology, which can also contribute to reducing the impacts of construction, but transportation can jeopardize overall reductions. Prefabricated housing plants are scarce and serve wide distribution areas, including overseas transportation to developing countries. A comprehensive assessment of transport related impacts in prefabricated construction is lacking and, in particular, the environmental impacts trade-offs of modular houses need to be thoroughly investigated, which is one of the main motivations of this article.

2. Model and inventory of a prefabricated house

In response to the research gaps identified and discussed in section 1, a case study was selected aiming at assessing a representative modular house manufactured in Europe with a high degree of prefabrication, for which primary data was collected for fabrication, including alternative structural materials, house sizes, and final house locations. Therefore, using scenario analysis, the assessment of the Moby house has been generalized with additional production options and for broader applicability to be representative of prefabricated modular houses currently produced in Europe.

A cradle-to-site model of a prefabricated modular house was implemented to the following phases: i) materials production, ii) transport of materials and workers to plant, iii) module production on the plant, iv) transport of modules, workers and material to the construction site and v) on-site modules assemblage and finishes. The prefabricated house – named Moby – is a detached, one-store, modular house developed by a Portuguese company (CNLL Ltd). It is based on the production concept of prefab industrialized modules (referred to as "core") and an onsite personalized assemblage and finishing (referred as "shell"). It is built in two phases: first $2.5 \times 7.5 \times 3.6$ m modules are produced in the plant; second, the modules are transported to site, assembled and finished. The modules can be combined into different house size, typically from one-bedroom to four-bedroom (details described in section 2.2.2). Fig. 2 illustrates the system boundary of the assessment.

2.1. Embodied energy and GHG

Embodied energy (EE) is the energy required to extract, produce and transport building materials (in a "cradle-to-site" assessment); operation energy refers to the energy used during the use phase (Bastos et al., 2013; Thormark, 2002). Similarly, embodied GHG estimates the GHG intensity from the extraction of raw materials to the building site, and operation GHG accounts for GHGs released into the atmosphere during to use phase. The EE measures only the non-renewable primary energy, i.e., EE does not include renewable energy, since the focus should be in non-renewable energy (Malça and Freire, 2006) and there is no consensus on how to estimate primary energy values of renewable energy (Molenbroek et al., 2011). Carbon and Energy are two metrics often used in literature to assess buildings' impacts (also for prefabrication; Aye et al., 2012; Bonamente et al., 2014; Zabalza Bribián et al., 2009), and some authors have discussed that these metrics can be a proxy for other environmental impact categories (Huijbregts et al., 2010), particularly in the LCA of buildings (Monteiro and Freire, 2012), but differences in results (for example regarding toxicity) can occur.

In this paper, the embodied energy (EE in MJ/kg), and GHG emissions (in kg CO_2eq/kg) of the Moby prefabricated house were calculated using the Inventory of Carbon and Energy (ICE) Version 2.0. (Hammond and Jones, 2006). ICE is a cradle-to-gate database for construction materials, with EE and CO_2eq values for most of the conventional building materials. The main assumptions of the ICE database for the three most significant materials in the Moby house (steel, concrete, and wood) are described below. For timber, biogenic carbon flows and carbon sequestration are excluded from the data. For concrete, the ICE uses data from the British Cement Association data (that excludes the re-carbonation of concrete in use, which is application dependent), which was used as a proxy for EU average. For steel, ICE data has been derived from the World Steel Association life cycle inventory, and we considered an EU average recycled content. Data for electricity production in Portugal was taken from Garcia et al. (2014) and fuels for transportation was from Spielmann et al. (2007). GHG emissions were based on the Intergovernmental Panel on Climate Change (IPCC) method v1.02, with a 100-year time horizon (IPCC, 2007).

2.2. One-bedroom Moby

A one-bedroom Moby with three modules and a total floor area of 56 m^2 was assessed as the base-case house. The floor plan, elevations and one picture are presented in Fig. 3. Four house sizes (from the 1-bedroom to the 4-bedroom house) will be presented in subsection 2.2.2.

Table 2 presents the inventory of producing the one-bedroom Moby, including the EE and GHG of materials and electricity.

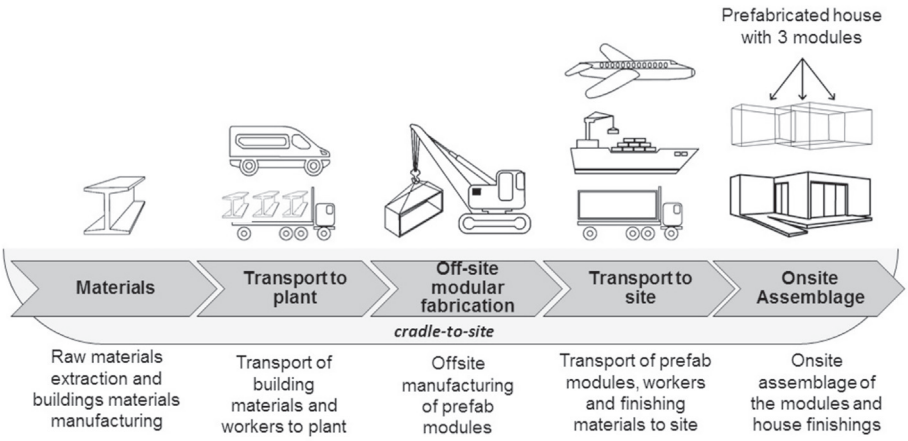
Prefabricated house with 3 modules
Materials
Transport to plant
Off-site modular fabrication
Transport to site
Onsite Assemblage
cradle-to-site
Raw materials extraction and buildings materials manufacturing
Transport of building materials and workers to plant
Offsite manufacturing of prefab modules
Transport of prefab modules, workers and finishing materials to site
Onsite assemblage of the modules and house finishings

Fig. 2. System boundary: Moby house "cradle-to-site" assessment.

Fig. 3. Floor plan, elevations and one picture of the one-bedroom Moby house.

Primary data for the foreground processes (transport, manufacturing and assemblage phases) was collected by the authors who were part of the Moby design team, with interviews to the manufacturing team and from the design project (implementation detailed drafts, shop drawings and bill of quantities). The electricity input for the prefabrication of one Moby modules at the plant was calculated based on the plant electricity bill and the number of modules being produced.

The inventory of the modular house is organized in two main parts:

- the core, which includes foundations, the primary structure of the modules, exterior wall, floor, roof and infrastructures for water, gas, electricity, and rain drainage systems.
- the shell, which includes exterior wall and floor finishes, interior walls, doors, windows and other elements (baseboard and cornices, sanitary equipment, wardrobe, kitchen, and bathroom cabinet).

2.3. Moby structure, size, and location

Four alternative structural materials, four house sizes, and seven final locations were comparatively assessed as described below.

2.3.1. Structural materials

Four alternative structural materials were analyzed: steel (base-case); concrete; timber and light steel framing (LSF). Table 3 details the weight (total and only the structure) of the one-bedroom Moby as well as the embodied energy and GHG of the four structural materials.

2.3.2. Moby house size

Four house sizes (bedroom number) were analyzed with the aim of assessing the influence of house size on impacts. The one-bedroom Moby has three modules and 56 m^2 of gross floor area, which can be expanded (as needed) by adding further modules. Floorplan and modules schemes for four layouts (different number of rooms, area, and inhabitants) are presented in Fig. 4. The corresponding inventory is presented in Table 4.

2.3.3. Final house location

Seven alternative final locations were analyzed to understand the influence of distance from plant to site. Three national locations: north of Portugal (city of Aveiro, base-case), center (Lisbon) and south (Faro), as well as four international locations: Paris,

Table 2
Inventory of the production of one-bedroom Moby: a) materials (core and shell); b) electricity for modules production.

	a) materials	weight kg	embodied energy[a] MJ kg^{-1}	embodied GHG[a] $kgCO_2eq\ kg^{-1}$
CORE		8325		
Foundation	Steel	1692	25.3	1.95
Structure	Steel	642	25.3	1.95
Exterior wall	Steel	713	25.3	1.95
	Plasterboard	704	6.8	0.39
	Polyurethane rigid	217	101.5	4.26
	Polyvinyl chloride (PVC)	404	77.2	3.10
	Rockwool	67	16.8	1.12
	Stainless steel	14	56.7	6.15
Floor	Aluminum	256	155.0	9.18
	Bitumen	215	51.0	0.49
	Steel	713	25.3	1.95
	Medium-density fiberboard (MDF)	576	11.0	0.39
	Rockwool	92	16.8	1.12
Celling	Steel	578	25.3	1.95
	Plasterboard	863	6.8	0.39
	Polyurethane rigid	118	101.5	4.26
	Polyvinyl chloride (PVC)	270	77.2	3.10
	Rockwool	92	16.8	1.12
Infrastructure	Bronze	1	69.0	4.00
Water supply	Copper	4	42.0	2.71
Gas supply	Polyethylene (LDPE)	4	83.1	2.54
Electricity	Polyvinyl chloride (PVC)	79	67.5	3.23
Rain drainage sewage	Zinc	10	53.1	3.09
SHELL		4126		
Exterior wall finishing	Cement	466	4.5	0.74
	Expanded polystyrene	124	88.6	3.29
	Fiberglass	17	28.0	1.35
	Paint	150	70.0	2.91
	Plaster	466	1.8	0.13
Interior wall	Steel	12	25.3	1.95
	Paint	45	70.0	2.91
	Plasterboard	317	6.8	0.39
	Rockwool	124	16.8	1.12
Floor finishing	Wood laminated flooring	308	12.0	0.42
	Polyethylene	27	83.1	2.54
	Timber	45	10.0	0.31
	Varnish	3	50.0	5.35
Doors	Brass	1	44.0	2.64
	Laminated veneer lumber	19	9.5	0.33
	Plywood	4	15.0	0.45
	Veneer	6	9.5	0.33
Windows	Extruded aluminum	147	154.0	9.08
	Glass	858	15.0	0.91
	Brass	15	44.0	2.64
Other element	Ceramic	137	29.0	1.61
Baseboard and cornice	Aluminum	68	155.0	9.16
Bathroom equipment	Resin	34	11.0	0.70
Kitchen cabinet	Medium-density fiberboard (MDF)	708	11.0	0.39
Countertop	Nickel	3	164.0	12.40
Lighting	Stainless steel	11	56.7	6.15
	Timber	12	10.0	0.31

b) modules production	kWh	MJ kWh^{-1}	$kgCO_2eq\ kWh^{-1}$
Electricity consumed from the grid[b]	12 000	4.4	0.36

[a] (Hammond and Jones, 2006).
[b] (Garcia et al., 2014).

Table 3
One-bedroom Moby with alternative structural materials.

	total weight kg	structure weight kg	%	embodied energy MJ/kg	embodied GHG kgCO2eq/kg
Steel (Base case)	12 450	2647	21%	25.3	1.95
Concrete	52 377	42 573	81%	2.3	0.24
Timber	13 077	3273	25%	10.0	0.31
LSF	11 196	1393	12%	13.1	0.72

Fig. 4. Floor plan, elevations and one picture of the one-bedroom house.

Table 4
Inventory of Moby house types (1- to 4-bedrooms).

	1-bedroom		2-bedroom		3-bedroom		4-bedroom	
	weight kg	%	weight kg	%	weight kg	%	weight kg	%
Foundations	1692	14%	2256	13%	2820	13%	3384	13%
Structure	642	5%	856	5%	1070	5%	1284	5%
Exterior wall	2119	17%	2435	14%	2653	13%	2900	12%
Floor	1852	15%	2469	14%	3086	15%	3703	15%
Celling	1921	15%	2561	15%	3202	15%	3842	15%
Infrastructure	99	1%	132	1%	165	1%	198	1%
Exterior wall finishing	1222	10%	1405	8%	1531	7%	1673	7%
Interior wall	499	4%	1773	10%	2609	12%	3259	13%
Floor finishing	383	3%	511	3%	638	3%	766	3%
Doors	78	1%	156	1%	234	1%	234	1%
Windows	1004	8%	1358	8%	1535	7%	1863	7%
Other elements	988	8%	1317	8%	1647	8%	1976	8%
TOTAL	**12 499**		**17 229**		**21 190**		**25 081**	

Casablanca, Luanda, and Rio de Janeiro, which represent potential markets for modular houses.

Transport has two main stages: transport to plant (of workers and materials) and transport from plant to site (of modules, workers and finishing materials). The transport of materials to plant requires one trip of a 3.5–16t lorry, fleet average (Spielmann et al., 2007) and a 50 km distance. The transport of six workers to plant was done in three passenger cars at a 10 km distance. Regarding transport from plant to site, modules were transported each one individually in a lorry with load capacity over 28t, fleet average, with an empty return (Spielmann et al., 2007). When overseas locations were considered, transport was done between ports in transoceanic vessels. To the port and from the port, modules were individually transported in a 28t lorry fleet average

(Spielmann et al., 2007). Finally, finishing materials were considered to be locally acquired, and a single trip in a 3.5–16t lorry (fleet average at a generic 50 km distance) was considered (Spielmann et al., 2007). The transport of six workers from the plant to the domestic sites was done in a passenger van (Spielmann et al., 2007). For overseas locations and Paris city, two workers (supervisors) were transported by plane and a team of four hired locally.

3. Results

The main results are presented in this section: for the base case scenario (one-bedroom Moby) in section 3.1 and for the scenario analysis in section 3.2 (alternative structural materials (3.2.1), different house sizes (3.2.2), and final house location (3.2.3)).

3.1. One-bedroom Moby

Fig. 5 shows EE and GHG for the one-bedroom Moby. Materials production impacts were calculated by multiplying quantities of materials with the corresponding embodied energy and GHG data. Materials production is the most important phase in a cradle-to-site assessment (80% of EE and GHG) followed by modules production (12% of EE, 16% of GHG). Modules production shows an inversion in the relation between GHG and EE relatively to materials production, due to the relatively low EE of modules production (mainly electricity generation: 4.4 MJ kWh^{-1}).

Results for the materials production phase are breakdown in Table 5. Most of the impacts are associated with the core (more than 70% of EE and GHG). Floor composition and exterior wall composition have similar impacts (around 20%) followed by foundations and roof composition (both around 15%). The sum of transport to plant, transport to the site (city of Aveiro), and assemblage and finishing phases accounts for less than 5% of total impacts.

3.2. Scenario analysis

The results for the alternative scenarios for structural materials (steel, timber, LSF and concrete), house size (from 1- to 4-bedroom house) and final locations (Aveiro, Lisbon, Faro, Casablanca, Paris, Luanda, and Rio de Janeiro) are discussed in this section.

3.2.1. Structural materials

Fig. 6 compares the materials production phase impacts of the one-bedroom Moby with different materials for the structure. The structures with light steel framing (LSF) or timber have the lowest GHG and EE impacts, a reduction of about 20% GHG and 10% EE, relatively to the steel structure (base-case). Concrete structure has the highest impacts: more 24% GHG and 9% EE relatively to the steel structure. Similar findings were presented by Cabeza et al. (2014) (in a revision paper about LCA of buildings) that concluded that concrete and steel were responsible for most of the buildings' impacts. It can also be seen in Fig. 6 that concrete shows an inversion in GHG/EE relatively to the other three structural materials due to a higher GHG/EE ratio for concrete: GHG/EE (gCO_2eq/MJ) is 100 for concrete, 80 for steel; 50 for LSF; and 30 for timber.

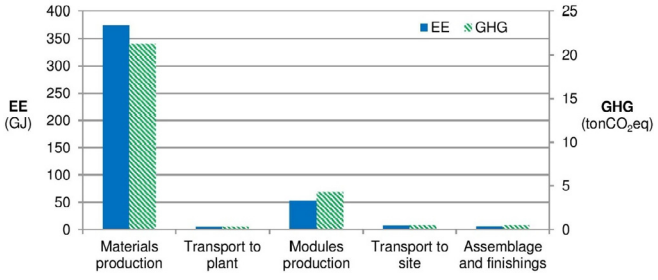

Fig. 5. Cradle-to-site EE and GHG of the one-bedroom Moby.

Table 5
Materials production phase: contribution to impacts.

	Embodied Energy (EE)		Greenhouse Gases (GHG)	
	MJ	% of total	$kgCO_2eq$	% of total
CORE	**274 852**	**73%**	**15 948**	**75%**
Foundations	42 802	11%	3299	15%
Primary structure	16 244	4%	1252	6%
Ext. wall composition	77 948	21%	4005	19%
Floor composition	76 521	20%	4171	20%
Roof composition	54 833	15%	2907	14%
Infrastructure	6505	2%	314	1%
SHELL	**99 516**	**27%**	**5339**	**25%**
Exterior wall finishing	24 907	7%	1273	6%
Interior wall	7681	2%	417	2%
Floor finishing	6546	2%	229	1%
Doors	328	0%	12	0%
Windows	35 462	9%	2113	10%
Other elements	24 592	7%	1295	6%
TOTAL	**374 368**	**100%**	**21 288**	**100%**

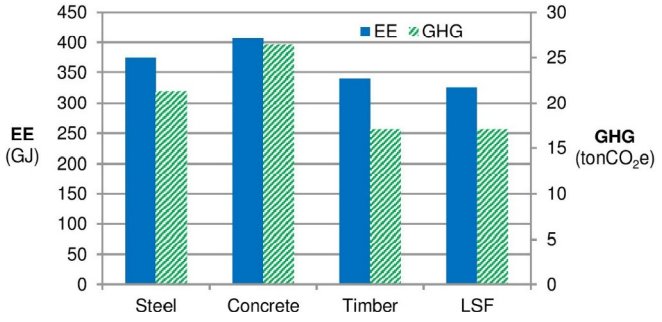

Fig. 6. Materials production phase impacts for the one-bedroom Moby.

3.2.2. House size (number of bedrooms)

Fig. 7 compares the EE and GHG impacts of four house sizes (different number of bedrooms and inhabitants). Fig. 7a) reports total values while Fig. 7b) relative values for two alternative functional units: one inhabitant (hab); and one m^2 of gross floor area. The house embodied impacts per inhabitant reduce significantly with the area increase (and inhabitants in the house), but not the impacts per m^2. This is because the increase in impacts is related with area increase, but the number of inhabitants rises more sharply than the area. Thus, a larger house leads to lower impacts per inhabitant but similar impacts per m^2.

3.2.3. Final house location

Fig. 8 shows the impacts of transportation of modules, workers and finishes of the "one-bedroom Moby" for seven final locations (four national and three international). In the base-case scenario (steel structure, one-bedroom house located in Aveiro) transport to site represents 2% of total impacts. However, Fig. 8 shows that for other cases, transport to final location can represent a significant share of total impacts, being as much as 25% of EE and 27% of GHG for Rio de Janeiro. The transportation impacts to final house location do not rise linearly with distance but are also dependent on transport mode. For example, transport to Faro (500 km distance,

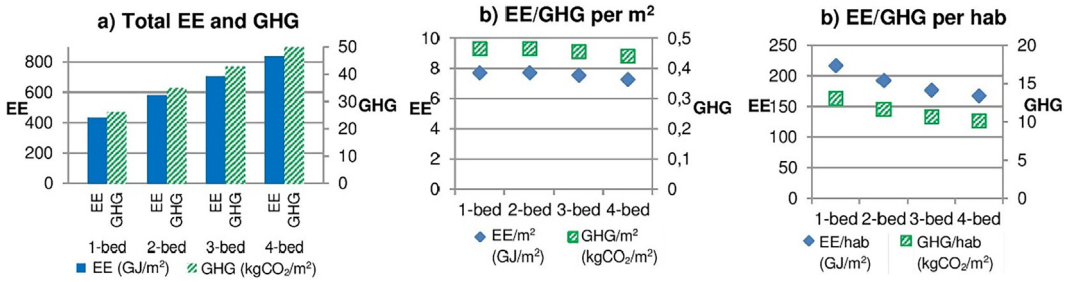

Fig. 7. a) Embodied energy and GHG intensity for the four houses and b) The influence of house size on impacts for two alternative functional units.

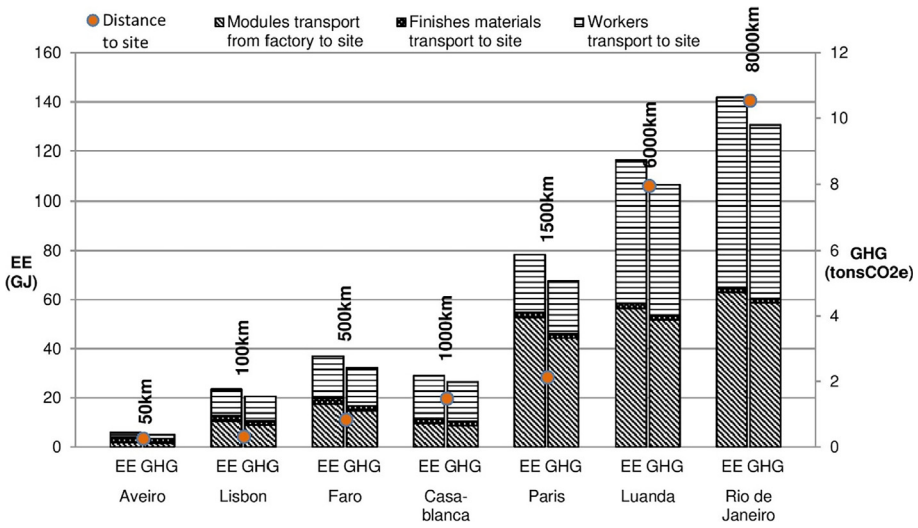

Fig. 8. Embodied Energy (EE) and GHG for the transport for final house location.

by land) represents 8–9% of total impacts, while to Casablanca (1000 km distance, by water) only 6–7%.

4. Conclusions

This study has assessed the embodied energy and GHG of a modular prefabricated house named Moby, addressing alternative structural materials (steel, concrete, timber, and LSF) and alternative house sizes (number of bedroom and inhabitants). Alternative house final locations have also been assessed to analyze transport related impacts, which has been much neglected in previous studies of prefabricated buildings.

The embodied impacts calculated (cradle-to-site) for the Moby house show that materials production is the most important contributor (64–90% of EE and 59–87% of GHG). For the base-case scenario (1-bedroom, steel structure, located in Aveiro) materials production represents about 80% of total impacts (and around 3/4 is from the Moby "core"). The second most important phase is modules' production, but it should be noted the low level of industrialization of prefabricated companies, as discussed by others (Pons and Wadel, 2011).

The impacts of transportation (of modules, workers and finishes) vary significantly for the various house final locations assessed: from 2% (for Aveiro, the base-case) to around 26% (for Rio de Janeiro) of total embodied impacts. Transport-related impacts can be critical as may balance the potential benefits of prefabrication, particularly for modular prefabrication due to the high volume of the finished modules. The embodied impacts increase with the house size (number of bedrooms and inhabitants); however, a larger house leads to lower impacts per inhabitant, but similar impacts per m^2 (of gross floor area), since the number of inhabitants rises more sharply than area.

The results presented in this article for the various alternatives and scenarios assessed show some variation, but fit the ranges presented in the literature: embodied energy (EE) varies from 7489 MJ/m^2 to 10 378 MJ/m^2 (from Aveiro to Rio de Janeiro); and GHG from 454 $kgCO_2eq/m^2$ to 647 $kgCO_2eq/m^2$, while EE in literature varies between 1750 MJ/m^2 (Heravi et al., 2016) and 14 400 MJ/m^2 (Aye et al., 2012); and GHG varies between 211 $kgCO_2eq/m^2$ (Islam et al., 2016) and 1000 $kgCO_2eq/m^2$ (Vitale et al., 2018). A comparison with other modular prefabricated buildings is limited since only Monahan and Powell (2011), and Quale et al. (2012) addressed modular, and the latter performed a partial assessment of the building (considering only the materials that were different between prefab and conventional). Monahan and Powell (2011) calculated embodied impacts for a modular timber frame house in the USA ranging from 5700 to 7700 MJ/m^2 and from 405 to 535 $kgCO_2eq/m^2$, likewise to those calculated for the Moby house with timber structure (7642 MJ/m^2 and 425 $kgCO_2eq$) for similar plant-to-site distances (around 200 km). The impact for Moby built in Aveiro (with alternative structural materials) range from 7100 to 8500 MJ/m^2 and from 405 to 571 $kgCO_2eq/m^2$, which is a lower range of impacts than those for non-prefabricated houses (presented in Table 1: 8200–9600 MJ/m^2 and 578–752 $kgCO_2eq/m^2$).

As discussed by Bastos et al. (2015), any LCA study for buildings involve a number of assumptions and simplifications. We have assumed our study is static and technological progress (hardly predictable) was not considered. Evolving production technology and increasing the scale production might lead to gains in efficiency

and to the reduction of embodied impacts, but this was not addressed due to lack of information. We have implemented a detailed building construction model using primary data collected from actual processes, but secondary data (for materials) comes from the ICE Version 2.0 database (assumptions discussed in section 2.1). Assumptions for the transport stages were discussed in section 2.3.3, but it should be added that future efficiency or electrification of the transport fleet could decrease related burdens. Our study is cradle-to-site and processes occurring during use, and end-of-life phases are beyond the boundary. However, issues related with concrete (an alternative structure material in the scenario analysis) during use and demolition phase, need further discussion, as follows. Concrete carbonation – a reaction occurring under natural conditions to cement – naturally reabsorbs CO_2 (Lee et al., 2013; García-Segura et al., 2014; Yang et al., 2014), reducing the overall GHG intensity of concrete house. However, carbonation process is highly dependent on the type and quality of the cement, the service life and environmental alternatives (García-Segura et al., 2014) thus it is difficult to be accounted for. Despite these assumptions and simplifications, the analysis provides a comprehensive assessment of a modular prefabricated building and the importance of transportation in a cradle-to-site assessment. Lastly, further studies are needed to assess the full life-cycle of prefabricated modular houses (for different climatic regions), and a comparison with conventional buildings should be performed.

To improve the environmental performance of prefabricated houses, we recommend to focus on selecting less energy and carbon-intensive materials and reducing the impacts of transportation of modules and workers by: i) reducing distance from plant to site; ii) choosing less energy intensive transport modes; iii) transport prefabricated panels instead of modules; and iv) selecting local materials and workers to complete the onsite assemblage stage.

Acknowledgments

Vanessa Tavares acknowledges financial support from the Portuguese Science and Technology Foundation through grants PD/BD/128067/2016. This work has also been supported by FCT project StreamLAB (MIT-EXPL/SUS/0013/2017), and by Project SET-LCA (CENTRO-01-0145-FEDER-030570), co-funded by FEDER and FCT. The research presented in this article was developed under the framework of the Energy for Sustainability Initiative of the University of Coimbra and the MIT Portugal Program.

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